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NOTE

Forest structure following tornado damage and salvage logging in northern Maine, USA

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Abstract: Understanding forest structural changes resulting from postdisturbance management practices such as salvage logging is critical for predicting forest recovery and developing appropriate management strategies. In 2013, a tornado and subsequent salvage operations in northern Maine, USA, created three conditions (i.e., treatments) with contrasting forest structure: blowdown, blowdown + salvage, and control (undisturbed). We sampled forest structure in five stands representing each of these three treatments. Our results document obvious and predictable changes to forest structure caused by the blowdown and salvage operations; however, they also include unexpected findings: downed coarse woody debris volume remained quite high in the salvaged areas, although its vertical distribution was markedly reduced; salvage operations did not reduce fine woody debris volume; and the salvage operation itself reduced the abundance of upturned root masses. Our study contributes to a growing body of literature highlighting the fact that outcomes of salvage operations vary considerably from situation to situation. Nevertheless, they suggest that salvage logging has important implications for residual stand structure and regeneration potential and that these implications should be considered carefully when weighing postdisturbance management options.

Key words: fire risk, fuel loads, pit-and-mound, *Picea rubens*, wind disturbance, woody debris.

Résumé : Il est essentiel de comprendre les changements dans la structure de la forêt qui résultent des pratiques d'aménagement, telles que la coupe de récupération, appliquées à la suite d'une perturbation pour être en mesure de prédire le rétablissement de la forêt et d'élaborer des stratégies d'aménagement appropriées. Une tornade survenue en 2013 et les opérations subséquentes de récupération dans le nord du Maine, aux États-Unis, ont engendré trois types de situations (c.-à-d. traitements) comportant différentes structures de la forêt : chablis, chablis + récupération et témoin (non perturbée). Nous avons échantillonné la structure de la forêt dans cinq peuplements représentatifs de chacun de ces trois traitements. Nos résultats témoignent des changements évidents et prévisibles dans la structure de la forêt causés par le chablis et les opérations de récupération. Cependant, ils incluent également des surprises : comparativement au chablis non récupéré, la coupe de récupération n'a pas réduit davantage l'abondance des arbres vivants; le volume de débris ligneux au sol est demeuré relativement élevé dans les zones de récupération bien que sa distribution verticale ait été nettement réduite; les opérations de récupération n'ont pas réduit le volume de débris ligneux fins; et l'opération de récupération elle-même a réduit l'abondance des masses de racines renversées. Notre étude s'ajoute au nombre croissant de publications mettant en évidence le fait que les résultats des opérations de récupération varient considérablement d'une situation à l'autre. Néanmoins, ils indiquent que la coupe de récupération a d'importantes conséquences sur la structure et la capacité de régénération du peuplement résiduel et que ces conséquences devraient sérieusement être prises en compte lorsque vient le temps d'évaluer les options d'aménagement à la suite d'une perturbation. [Traduit par la Rédaction]

Mots-clés : risque d'incendie, charges de combustibles, creux et buttes, *Picea rubens*, perturbation causée par le vent, débris ligneux.

Introduction

Natural disturbances alter forest structure, function, and composition across a range of scales. Severe wind storms in particular damage or kill standing trees, creating pulses in downed woody debris and potentially causing shifts in species composition (Everham and Brokaw 1996). The windthrown, damaged, and stressed trees also provide an influx of easily exploitable habitat for bark beetle (Scolytinae) populations to build and potentially move into healthier trees (Nováková and Edwards-Jonášová 2015). In New England, USA, windstorms are the prevalent natural disturbance agent, although historically they have only rarely been stand-replacing events. Early Government Land Office records from the region suggest that stand-replacing windstorms had point return intervals in excess of 800 years (Lorimer 1977). Instead, historical windstorms more frequently caused partial canopy mortality, typically resulting in less than 35% of canopy loss per decade (Fraver et al. 2009).

One post-windthrow management strategy increasingly under scrutiny is that of salvage logging. Although primarily used to mitigate economic losses following major disturbance, salvage logging has also been justified on the basis of reducing fuel loads and fire risk (Johnson et al. 2013), promoting forest regeneration (Sessions et al. 2004), and reducing the risk of bark beetle outbreaks (Stadelmann et al. 2013). The ability of salvage logging to achieve these secondary objectives remains controversial; in fact, it may at times increase fuel loads (Dunn and Bailey 2015), impede

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natural regeneration (Nováková and Edwards-Jonášová 2015), alter regeneration potential (Palik and Kastendick 2009; McIntosh and Macdonald 2013), and reduce the abundance of disturbance-generated biological legacies such as surviving trees, snags, and coarse woody debris (CWD) (Lindenmayer et al. 2008; Dunn and Bailey 2015). Further, the cumulative impact of both windthrow and salvage very soon thereafter may create conditions not predicted from our knowledge of these disturbances individually (Peterson and Leach 2008).

A recent series of events in northern Maine, USA, provides an opportunity to evaluate the impacts of stand-replacing wind damage followed by salvage logging in a region unaccustomed to windstorms of this severity. In July 2013, a tornado with wind speeds exceeding 40 m·s^{-1} affected a roughly 200-ha swath of forest land in north-central Maine, causing extensive canopy loss over much of that area. Portions of the affected area were salvaged that winter (2013–2014) for the purpose of forestalling economic losses; other portions were left nonsalvaged as demonstration sites. Because of the sharp delineation of the tornado-damaged area, most nearby forest stands were unaffected by the event. This situation conveniently created three conditions (treatments) that we can assess with respect to forest structure: blowdown, blowdown + salvage, and control (undisturbed).

Our overarching objective was to assess the structural changes caused by the tornado itself, as well as the tornado combined with salvage logging, relative to the undisturbed forest condition. Our specific objectives were as follows: (*i*) assess differences in living tree, snag, and woody debris (i.e., forest fuel) attributes between treatments; and (*ii*) insofar as salvage operations are at times assumed to function as fuel-reduction treatments, determine the extent to which salvage logging reduced the arrangement and vertical distribution of fuels. Ours is one of few contemporary studies of salvage logging in the region, and the affected mixed-species conifer forests are typical for northern New England and the Maritime Provinces, making this setting ideal for evaluating forest response to disturbance relevant to the region.

Methods

Field sampling

Our study took place within the Scientific Forest Management Area (SFMA) of Baxter State Park, in northcentral Maine, USA. This portion of the park has been set aside since 1955 to showcase sustainable, scientifically sound forest management, which began ca. 1980. Mean annual temperatures range from –10.0 °C in January to 19.8 °C in July, with an annual mean of 5.3 °C. Precipitation is evenly distributed throughout the year, with an average of 1076 mm annually. The topography of the SFMA is undulating, with elevations ranging from 244 to 390 m a.s.l. Soils are derived from glacial tills typical of the region. Forest stands in this portion of the SFMA are dominated by red spruce (*Picea rubens* Sarg.), with lesser components of balsam fir (*Abies balsamea* (L.) Mill.), northern white-cedar (*Thuja occidentalis* L.), eastern white pine (*Pinus strobus* L.), and red maple (*Acer rubrum* L.).

Each of the three treatments — blowdown, blowdown + salvage, and control (undamaged) — included five replicate stands. The salvage was an operational stem-only harvest (using a fixed-head cut-to-length processor and forwarder, with slash left on-site) conducted during the winter of 2013–2014. It conveniently created a patchwork of salvaged and nonsalvaged stands large enough for study within the tornado path. Five undamaged control stands were chosen to be as close to the tornado path as possible. We assume that prior to the tornado, stands were generally similar in structure and developmental stage, which is partially supported by pre-tornado (2009 and 2010) data available for four stands (two blowdown, two blowdown + salvage). The mean density of these stands was 584 trees·ha^{-1} (median 556), while the mean for the control stands was 705 trees·ha^{-1} (median 600). However, all of the blowdown + salvage stands and two of the blowdown stands had a prior history of light partial harvests (thinning by removing small stems) roughly 20 years before the tornado; the remaining stands were not thinned. Because the prior partial harvests had little effect on stand density and no apparent effect on woody debris abundance in the blowdown stands, their effect was disregarded in further analyses. All stands were typed as softwood-dominated. In addition, our inventory data ultimately allowed us to assess pre-tornado composition distinctly for each treatment type. Overstory data from the control stands, stump data from the blowdown + salvage stands, and woody debris data from four of the five blowdown stands clearly indicate red spruce dominance (northern white-cedar exceeded red spruce in woody debris abundance at one stand).

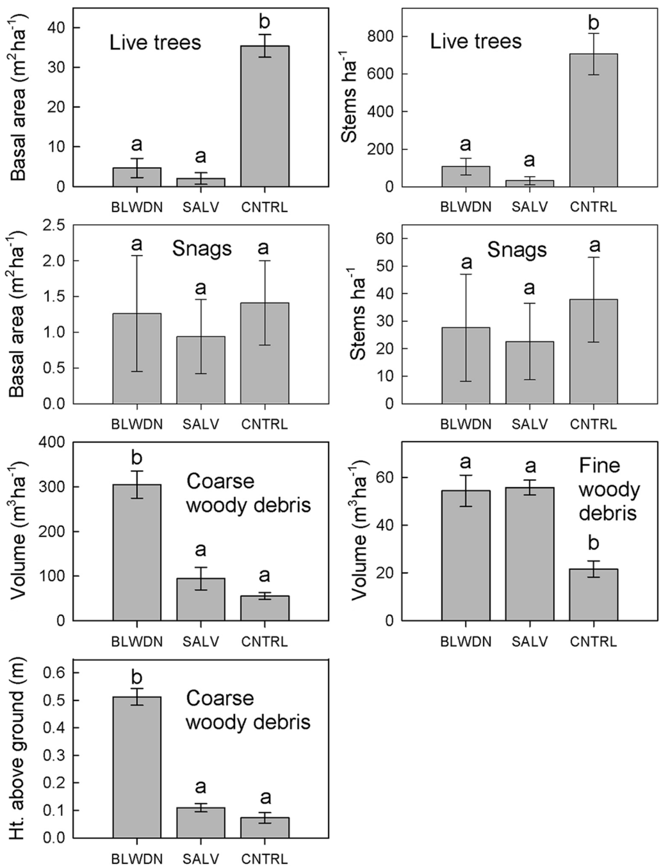
During the first field season (summer 2014) following the winter salvage, we established one circular 800 m^2 (16 m radius) research plot in each stand to characterize forest structure. This plot size follows SFMA's protocol for continuous forest inventory plots. In small stands (less than ca. 3 ha), the plot center was placed in the geographic center of the stand to avoid edge influence. In larger stands, the plot center was randomly selected using a GIS, avoiding locations within 50 m of the stand boundary. For each standing tree > 10 cm diameter at breast height (DBH), whether living or dead, we recorded species and DBH. In the salvaged stands, the species and top diameter of stumps were recorded. To estimate downed CWD (i.e., coarse fuels > 10 cm diameter) volume, we used the line intercept method (Van Wagner 1968) applied to three 40 m transects radiating spoke-like outward from the plot center at 0°, 120°, and 240°. The multidirectional, spoke-like arrangement mitigates variability when CWD pieces exhibit fairly uniform fall directions (Van Wagner 1968). For each CWD piece intersected by the sampling transect with a diameter ≥ 10 cm at the intersection, we recorded diameter at intersection, species, height above the forest floor, type of wind damage (uprooting vs. snapped, when possible), and decay class (five-class system of Sollins 1982). We recorded fine woody debris (FWD, i.e., fine fuels < 10 cm diameter) in four diameter classes: to 1 cm, 1–2.5 cm, 2.5–5 cm, and 5–10 cm along 2, 4, 6, and 8 m segments, respectively. These segments began at 10 m and again at 30 m distant from plot center along each of the three CWD transects. Thus, total FWD transect lengths sampled at each plot were 12, 24, 36, and 48 m, respectively, for the four diameter classes.

Data summarization and analyses

Woody debris volumes per hectare were determined as per Van Wagner (1968). For CWD, we reduced the volume of advanced-decayed pieces (decay classes 4 and 5) to account for their gradual collapse through decay (Spies et al. 1988), using reduction factors of 0.800 and 0.412 (classes 4 and 5, respectively; Fraver et al. 2013). For FWD, we used the quadratic mean diameters (QMD) within each size class for calculations, as recommended by Woodall and Monleon (2010). QMDs were based on ca. 1850 FWD diameters measured for this purpose on a subset of transects representing all three treatments. QMDs were 0.34, 1.63, 3.62, and 7.88 cm for the four classes, respectively.

All treatment effects on each of the response variables (living-tree density and basal area, snag density and basal area, CWD volume, CWD height above forest floor, FWD volume) were examined using separate mixed-model analyses of variance (ANOVA) in which treatment was considered as a fixed effect and stand (within treatment) was considered as a random effect. When significant treatment effects (α = 0.05) were detected, post hoc Tukey's honest significant difference tests were used to compare treatments. ANOVAs were conducted using SAS version 9.4 (SAS Institute Inc. 2013). Finally, although it is common practice to evaluate the influence of tree size and species on windthrow probability (Ruel 2000; Canham et al. 2001), we were not able to do so. The severity of the storm was such that too few trees remained standing to afford suitable sample sizes for such analyses.

Fig. 1. Forest structural attributes (mean ± standard error) by treatment (BLWDN, blowdown only; SALV, blowdown + salvage; CNTRL, undisturbed control). Ht., height. Means with different letters differ at $\alpha < 0.05$.



Results

Based on the structural attributes of the control stands, we estimate that the tornado significantly reduced living-tree basal area from a mean of 35.4 (median 34.4) to a mean of 4.7 $m^2 \cdot ha^{-1}$ (median 1.7) ($P < 0.001$; Fig. 1). It significantly reduced live tree density from a mean of 705 (median 600) to a mean of 108 $trees \cdot ha^{-1}$ (median 75) for control and blowdown stands, respectively ($P < 0.001$; Fig. 1). Living-tree basal area did not differ significantly between blowdown and blowdown + salvage treatments ($P = 0.71$), nor did living-tree density ($P = 0.73$; Fig. 1). In contrast, neither snag basal area nor snag density differed significantly between any of the treatments (all $P > 0.79$; Fig. 1). Wind-thrown trees were more likely to be uprooted (76%) than snapped (24%).

As expected, mean CWD (i.e., downed coarse fuel) volume was significantly lower in blowdown + salvage (94.3 $m^3 \cdot ha^{-1}$) than in blowdown (304.6 $m^3 \cdot ha^{-1}$) stands ($P < 0.001$) but did not differ between blowdown + salvage and control (55.4 $m^3 \cdot ha^{-1}$) stands ($P = 0.48$; Fig. 1). In contrast, FWD volumes did not differ significantly between blowdown + salvage and blowdown stands (55.8 and 54.4 $m^3 \cdot ha^{-1}$, respectively; $P = 0.97$), though both were significantly higher than the control (21.6 $m^3 \cdot ha^{-1}$) (both $P < 0.001$; Fig. 1).

Salvage operations resulted in CWD pieces being closer to the forest floor, an important consideration regarding fire behavior. The mean height of CWD pieces in the blowdown (0.51 m; median 0.4 m) differed significantly from that of the blowdown + salvage (mean 0.11 m; median 0 m; $P < 0.001$) and control (0.07 m; median 0 m; $P < 0.001$) stands (Fig. 1).

Discussion

Ours is one of few contemporary studies of salvage logging in New England, USA. Our design allowed us to evaluate forest structural differences between blowdown, blowdown + salvage, and undisturbed control stands. In many cases, the structural changes documented here were distributed among the three treatments in obvious ways; however, pair-wise comparisons revealed contrasts worth noting.

As expected, treatment differences suggest that the tornado dramatically reduced living-tree basal area (from ca. 35.4 to 4.7 $m^2 \cdot ha^{-1}$). Though comparable studies of tornado damage are not available for New England, this reduction is similar to that documented from a tornado in an eastern hemlock (*Tsuga canadensis* (L.) Carrière) – hardwood forest in northwestern Pennsylvania (Peterson and Pickett 1991) and is within the range of the severe tornados reported in a compilation of nine tornados in the eastern US (Peterson 2007). Treatment differences also suggest that the salvage operation did not further reduce living-tree basal area (2.0 $m^2 \cdot ha^{-1}$) relative to the blowdown (Fig. 1). Similarly, Man et al. (2013) found that salvage logging did not further reduce living-tree volume, although it did reduce living-tree density. Our finding may be attributed to the SFMA's "Protocols for Harvest Following Natural Disturbance," which recommends that operators retain an estimated 5% of the predisturbance live stocking, as well as all nonmerchantable stems. Given the severity of the tornado, this protocol limited opportunities for further removal of living trees.

Although we had expected fewer snags in the blowdown relative to the control (more expected to have been windthrown) and fewer still in the blowdown + salvage relative to other treatments (snags are easier to access during harvest), neither of these expectations were borne out by the data. Similarly, D'Amato et al. (2011) found that snag basal area did not differ between blowdown and control stands, and Man et al. (2013) found that neither snag volume nor density differed between blowdown and blowdown + salvage treatments. The latter study attributed the lack of difference to high variability in snag abundances within treatments. This explanation, combined with the overall low abundance of snags in our study, may in part explain the lack of differences evident in our results. Further, the similarity in snag abundance and basal area between blowdown and blowdown + salvage may be attributable to SFMA's salvage protocol (as above), which recommends that operators retain an estimated 4% of the predisturbance snag stocking, as well as all nonmerchantable snags. In contrast to our findings, Waldron et al. (2013) found that salvage logging reduced the number of snags relative to nonsalvaged blowdown.

Our finding that uprooted trees (76% of total windthrows) were more prevalent than snapped trees (24%) is also consistent with findings of tornado damage reported by Peterson and Pickett (1991) and Peterson (2007). The issue of uprootings vs. snaps has important implications for forest recovery, as several of our common tree species benefit preferentially from the exposed mineral soil on uprooting mounds resulting from windthrow. For example, the prevalence and enhanced survival of birch (*Betula*) seedlings on uprooting mounds is well documented (Hutnik 1952), and red spruce is also known to benefit from uprooting mounds (Smallidge and Leopold 1994).

We note, however, that the benefit of uprooted trees regarding potential seedling establishment and microtopographic heterogeneity (i.e., pit-and-mound structures) was diminished in the salvaged stands. Once the salvaged stems had been cut and removed, the root mass often hinged back to its original position under the force of gravity (authors' personal observation). In addition, operators often pushed the root mass back to its original position to facilitate ease of equipment operation (authors' personal observation). We estimate that ca. 50% of the upturned root masses were thus repositioned. Waldron et al. (2013) also report a reduction in pit area and number of pits and mounds in post-salvage windthrown areas, presumably for this same reason. This phenomenon precludes the formation of pit-and-mound microtopography, and it may confound the interpretation of historical windthrow and salvage operations at other sites.

Corresponding to the loss of living trees, CWD volume in the blowdown stands was over five times higher than that of the control stands (Fig. 1), with volumes dominated by nondecayed, blowdown-generated material. Similar CWD additions following blowdown have been reported by D'Amato et al. (2011). Assuming that the control stands approximate the pre-tornado conditions on other stands, our findings suggest that while salvage operations dramatically reduced CWD volumes, they still remained quite high (mean 94.3 $m^3 \cdot ha^{-1}$), in fact indistinguishable from those of the control stands (Fig. 1). Similarly, D'Amato et al. (2011) found no difference in CWD volume between control and blowdown + salvage stands, with both having volumes ca. 75 $m^3 \cdot ha^{-1}$. Priewasser et al. (2013) also reported high volumes (74.6 $m^3 \cdot ha^{-1}$) in post-windthrow salvaged stands in Switzerland, pointing out that these values are twice as high as those proposed for biodiversity conservation in central Europe (Müller and Bütler 2010). These high volumes could be explained in part by the operational difficulties of harvesting on-the-ground logs (Waldron et al. 2013). In addition, the salvage harvest documented here extended into the winter, such that snowfall had obscured harvested and delimbed logs (authors' personal observation), which further accounts for the high CWD volumes left on site.

Structural changes resulting from the salvage operation have important implications when viewed from a fuel-reduction perspective. We emphasize that this salvage operation's objective was to forestall economic losses from damaged merchantable timber; it was not intended as a fuel-reduction treatment. Purposeful and effective fuel-reduction treatments remove FWD (i.e., slash or fine fuels), as well as CWD (Fraver et al. 2011; Stephens et al. 2012). The fact that slash was not removed at harvest can clearly be seen by the similarity in FWD volumes between blowdown and blowdown + salvage stands (Fig. 1). The treatment of FWD in postdisturbance salvage operations is critical for reducing near-term fire hazard, given that these fuels largely govern ignition, spread rate, and fire-line intensity (Dodge 1972; Rothermel 1972). Nevertheless, our findings suggest that the salvage operation significantly reduced the vertical distribution of CWD (Fig. 1), which has two positive benefits related to fuel conditions. First, it results in greater fuel compactness (i.e., higher packing ratio), which lowers combustion efficiency by restricting airflow to the active fire (DeBano et al. 1998). Second, it places CWD pieces in contact with the forest floor (CWD in the salvaged areas had a median height of 0 m), which increases fuel moisture content (Hollis et al. 2011) and hastens decay (Næsset 1999). Although height was measured only for CWD, heights were similarly reduced for FWD (authors' personal observation). Finally, the spatial configuration of the salvaged and nonsalvaged stands in the SFMA, whether intentional or not, created a mosaic of patches that, in the event of fire, may impede fire spread through the landscape (Gaylor 1974; D'Amato et al. 2011).

Conclusions

Recent years have seen an increasing interest in postdisturbance forest management, which has highlighted controversies surrounding salvage logging (Lindenmayer et al. 2008). Salvage logging and the attendant controversies will likely persist, particularly given the projected increases in natural disturbance frequency and intensity (Dale et al. 2001; Beniston et al. 2007). One particular concern is that salvage operations diminish the abundance of biological legacies such as surviving trees, snags, and CWD (relative to undisturbed) (DellaSala et al. 2006; Waldron et al. 2013). The fact that salvage harvests may be exempt from regulations and guidelines that govern traditional harvests (Meadows 1998; Nappi et al. 2004) exacerbates this concern. However, these detrimental effects were not found in the current study: relative to the nonsalvaged blowdown treatment, salvage logging did not further reduce living-tree or snag abundance, and CWD abundance remained similar to that of the undisturbed control sites. The operation documented here was conducted under a preexisting salvage-harvesting protocol intended to retain some portion of living and standing dead trees, and the winter harvest meant that snowfall had obscured fallen and harvested stems, resulting in significant retention of CWD. In addition, the winter harvest (snow over frozen soils), as well as further protection of the forest floor by retained slash, would have minimized the soil damage often reported from salvaged sites (Fraver et al. 2011). As a result, this operation appears to be less intensive and presents fewer ecological concerns than previously reported salvage case studies (Lindenmayer et al. 2008).

Our study contributes to a growing body of literature that highlights the fact that outcomes of salvage logging vary considerably from situation to situation, making generalizations difficult. The outcomes strongly depend on type and severity of the initial disturbance, harvest objectives, equipment used, time of year when the harvests occurs, and whether or not slash is retained (Peterson and Leach 2008; Fraver et al. 2011; Royo et al. 2016). Nevertheless, the biodiversity implications (Lindenmayer et al. 2008), plant functional group response (Blair et al. 2016), and forest regeneration potential (Palik and Kastendick 2009; Parro et al. 2015) resulting from salvage operations should be considered carefully when weighing postdisturbance management options, given that the compositional and structural changes may have long-lasting consequences (Blair et al. 2016; D'Amato et al. 2016).

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